Sustainability of irrigated farming systems in a Tunisian region: A recursive stochastic programming analysis

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A B S T R A C T

The aim of this study was to evaluate the sustainability of farm irrigation systems in the Cébalat district in northern Tunisia. It addressed the challenging topic of sustainable agriculture through a bio-economic approach linking a biophysical model to an economic optimisation model. A crop growth simulation model (CropSyst) was used to build a database to determine the relationships between agricultural practices, crop yields and environmental effects (salt accumulation in soil and leaching of nitrates) in a context of high climatic variability. The database was then fed into a recursive stochastic model set for a 10-year plan that allowed analysing the effects of cropping patterns on farm income, salt accumulation and nitrate leaching. We assumed that the long-term sustainability of soil productivity might be in conflict with farm profitability in the short-term. Assuming a discount rate of 10% (for the base scenario), the model closely reproduced the current system and allowed to predict the degradation of soil quality due to long-term salt accumulation. The results showed that there was more accumulation of salt in the soil for the base scenario than for the alternative scenario (discount rate of 0%). This result was induced by applying a higher quantity of water per hectare for the alternative as compared to a base scenario. The results also showed that nitrogen leaching is very low for the two discount rates and all climate scenarios. In conclusion, the results show that the difference in farm income between the alternative and base scenarios increases over time to attain 45% after 10 years.

1. Introduction

In Tunisia, even if agriculture is the main water-consuming sector and accounts for 82% of total water demand; the irrigated lands represent only 8% of the cultivated area (Mediterra, 2008). Despite that, those lands have strong impacts on social and economic activities by ensuring for Tunisia 35% of total agricultural production, 95% of market gardening's production, 30% of the dairy products, and 23% of rural employment (Bouksila, 2011).

Economically, the Tunisian irrigated farm performance depends strongly on available and quality of water used to increase yields that would otherwise be limited by prevailing low rainfall (the mean annual rainfall is around 230 mm/year). Moreover, 47% of the ground water and 67% of the deep aquifers have salinity higher than 3 g/l increasing the risk of soil salinisation and then yield degradation (Bouksila, 2011). The soil salinisation may arise also from inappropriate crop management, such as amount and dates of irrigation, irrigation systems, or from deficiency in drainage networks.

The use of various chemicals, such as inorganic fertilisers, has also expanded enormously over the 20–40 years in the irrigated Tunisian areas. Between 1961 and 2000, the amount of fertilisers used in agriculture has increased from 4.9 to 38.3 kg/ha, respectively (Latiri, 2002). A large part of the aquifers of the irrigated lands is located in areas of intensive agriculture and ground water is increasingly contaminated with nitrates (Mediterra, 2008).

Overall, the climatic, soil and water resources and the farmers' practices may contribute in varying degrees to farm income establishment and soil salinisation and nitrogen leaching risks. In fact, the use of appropriate irrigation water for leaching salts in the root zone with suitable drainage systems is often recommended for increasing crop yields and then the farm income (Garcia-Sanchez et al., 2003; Flagella et al., 2004). However, some researchers also pointed causes for movement of soil nutrient such as N and K, and its limitations in fine-texture soils where it results in water logging (Kolahchi and Jalali, 2007). In fact, in several cases, due to a combination of relatively high inputs of fertiliser and an over-abundant supply of irrigation water to leach salt (which dissolves in the supplied water) from the upper soil layers, nitrogen may be leached as well (Hamdy and Habib, 1995; Feng et al., 2005).

Nevertheless, in many developing countries (including Tunisia) irrigation is costly and, therefore, farmers are obliged to reduce the amount of irrigation water applied to their crops. Consequently, nitrate (NO_3–N) leaching is reduced (Kessavalou et al., 1996; Ottman et al., 2000; Watts et al., 1991), but the salt content of the soil increases. Accumulation of salt in the soil may reduce its future potential production (Van Genuchten and Gupta, 1993; Konukcu et al., 2006). Hence, short-term objectives to increase farm income often conflict with long-term objectives to maintain soil fertility.

In semi-arid regions, with highly variable rainfall and environmental problems, stochastic dynamic programming (SDP) is the most widely recommended method for studying the effect of different water and nutrient management practices on farm performance (Blanco and Flichman, 2002; Trezos and Yeh, 1987; Li et al., 2006).

However, this method, which breaks down a multiple-decision problem into a sequence of sub-problems, is ideally suited for a time-sequence with few decision problems such as the allocation of reservoir water and forestry management (Boussard, 1971; Ahmed et al., 2004; Nandalal and Bogardi, 2007). For systems with a large number of state variables, e.g., agricultural management assessment with multiple forecast decisions, the SDP method requires too much computing time (Birge and Louveaux, 1988; Luo et al., 2003). Using the SDP method means that all potential inter-temporal farm decisions which depend on the state of the farming environment should be defined before running simulations. Thus, the number of decision steps will increase exponentially and hence the model's size ("curse of dimensionality") (Blanco and Flichman, 2002; Nandalal and Bogardi, 2007).

In practice, this technique requires limiting the possible values of the model's state and decision variables to a finite discrete set. The solutions obtained are therefore approximate and, in the case of non linear functions, the errors can be non-negligible (Huang and Loucks, 2000; Blanco and Flichman, 2002).

In order to overcome those difficulties, the aims of this study were to:

1. Resolve the "curse of dimensionality" problem by developing a new methodology based on a recursive stochastic programming method (RSP).
2. Use the RSP method to assess at short and long terms the sustainability of Tunisian farming systems.

2. Materials and methods

2.1. Study area: farmers' production strategies

The irrigated area of northern Tunisia is a place where such short-term and long-term objectives conflict. The Cebalat area totals 3200 ha and was created in order to reuse wastewater as irrigation for fodder and cereal crops near the capital, Tunis. This area is supplied by the effluents of three wastewater treatment stations situated near Tunis. Those stations treat each year almost 75% of total urban, domestic and industrial discharges coming from Tunis. They are equipped (the stations) to perform secondary treatment effective in reducing organic pollution (COD and BOD5) but insufficient to eliminate bacteria and parasites. Each year, only a small part of the water is pumped to irrigate the Cebalat area, the rest is directly rejected in the sea.

The use of treated saline wastewater in combination with a saline and shallow water table increased the risk of soil degradation (Hachicha and Trabelsi, 1993; Belhouchette et al., 2008). Long-term meteorological data indicated that the region is characterised by irregular and variable seasonal and yearly rainfall. The mean annual rainfall for the period from 1970 to 2000 is 475 mm/yr (σ = 133 mm/yr). Furthermore the distribution varies between fall (from September to December the mean rainfall is 201 mm), winter (from January to April the mean rainfall is 259 mm) and spring-summer (From May to August the mean rainfall is 25 mm). The pedological analysis of the study area revealed three soil types: vertic, calcareous, and weakly saline that are differentiated by their hydro-structural behaviour (Braudeau et al., 2001).

The area includes mainly mixed farms (arable and livestock) smaller than 20 ha, with a wide range of cropping system practices, i.e. crop rotations and the amount of water and nitrogen applied (Braudeau et al., 2001; Belhouchette, 2004). The traditional crop rotation system is based on rain-fed cereals including soft wheat (*Triticum aestivum*), barley (*Hordeum vulgare*) and oats (*Avena sativa*) and forage crops such as berseem (*Trifulium alexandrinum*) during the fall period (September–December). Irrigated alfalfa (*Medicago sativa*) and irrigated maize (*Zea mays*) and sorghum (*Sorghum vulgare*) for forage or human consumption are grown in the spring-summer period (May–August). Based on expert knowledge and farmers' practices, various representative crop activities were defined: (i) rain-fed winter cereals (wheat, barley and oats) followed by maize and sorghum (grain or forage) in the summer, and (ii) irrigated winter forage (mainly berseem) followed by summer fallow and alfalfa grown for 3–4 years. Both summer and winter cereal and forage crops are usually irrigated during the sowing and flowering periods. Crop yields vary from year to year depending on weather, soil type, and water and nitrogen management, e.g. the mean yield of soft wheat was 2 t/ha (σ = 1.25 t/ha) for the period 1995–2000 (Bahri 1994; Hachicha et al., 1997; Braudeau et al., 2001).

Faced with biophysical conditions (i.e. climate, soil and water quality), farmers are often forced to take decisions concerning: (i) the type of winter crops, their management practices and their allocated area will depend on the amount of rainfall in the fall period (September–December), i.e. often more barley and oats are cultivated than soft and durum wheat when the fall proves to be particularly dry. In addition, complementary irrigation is usually required in the fall period for sowing durum wheat, and (ii) the summer forage area depends mainly on fall and winter rainfall, i.e. after a wet fall and winter, the summer forage area is reduced as the production of winter forage (mainly berseem and alfalfa) is sufficient for summer feeding. After a dry fall or winter, farmers generally cut or harvest the cereals to use as forage during the spring and summer period and increase the area of forage crops during the summer.

2.2. Recursive stochastic programming method

2.2.1. Concept

The main difference between the RSP method (recursive stochastic programming) and the SDP (stochastic dynamic programming) one is the way that decisions feed back into the model. With the RSP approach optimisation is performed over a discounted flow of returns, and decisions are taken sequentially then adjusted as and when additional information is available.

In practice, with the RSP method, a first decision is made before the values of random variables are known. Then, after the random events have occurred and affected the related variables, a second decision is made in order to minimise penalties that may occur due to the first decision. The key idea is therefore that the decision-maker cannot fully anticipate the response of the system and must opt for an optimal decision with the information that he has (sub-optimal decision). Since the stochastic dynamic problem is solved by a sequence of inter-temporal optimisations, the RSP approach allows both short and long term decisions to be made simultaneously.

In practice, optimisation will be achieved after several iterations (Fig. 1). For the first iteration, the simulation horizon ($t = n$) will be

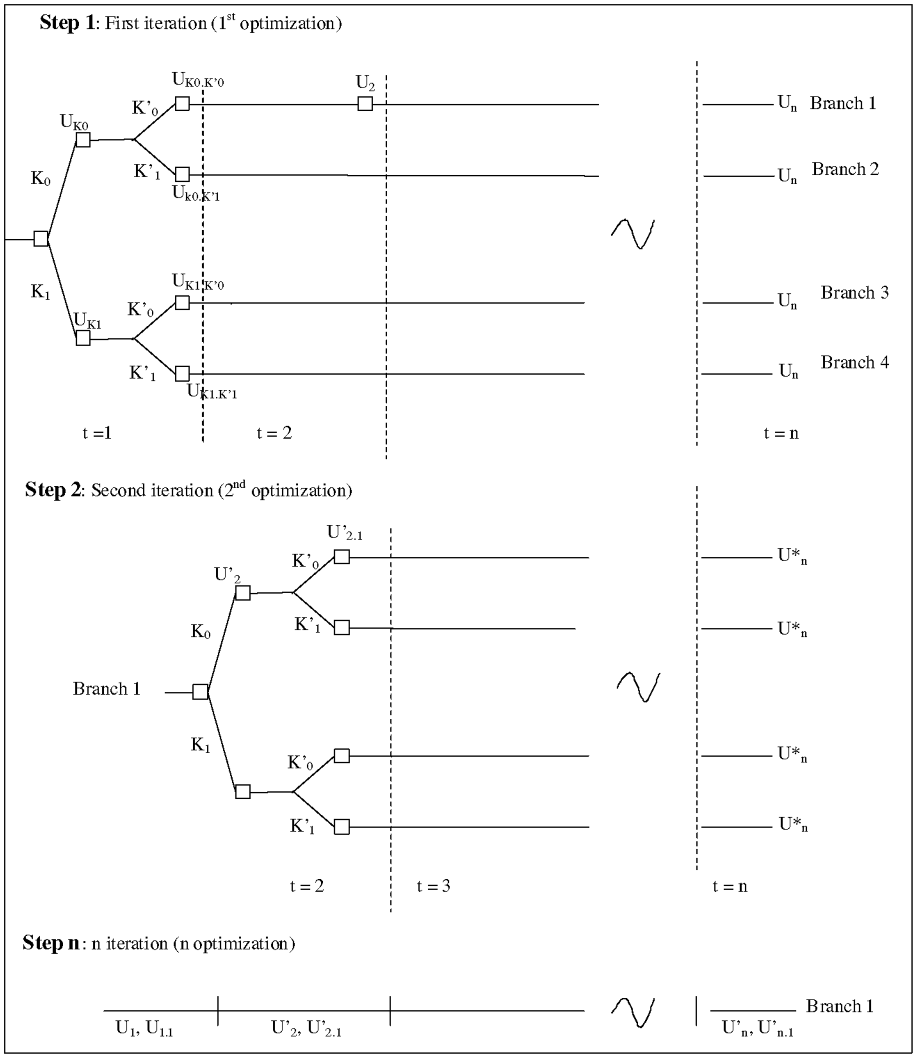

Fig. 1. Decision tree for the recursive stochastic problem. K: "state of nature" and U: decision variables. For step 1 there are two decision stages (stage 1: two decisions U_{K0} and U_{K1}, and stage 2: four decisions$U_{K0.K'0}$, $U_{K0.K'1}$, $U_{K1.K'0}$, $U_{K1.K'1}$) and two states of nature for each stage (stage 1: K_0 and K_1 and stage 2: K'_0 and K'_1). In step 1 and $t = 1$, the farmer takes a decision considering the stochastic event. $t = 2$ until $t = n$, for each branch, the farmer thinks in an average logic without stochastic events (U_2 until U_n). In step 2, uncertainty related to the stochastic event in the first stage will be cleared through the recursive process. Consequently, each branch will be considered as a new simulation with two stages as in the first iteration and with $t = n - 1$ as a simulation horizon. Simulation stops after n iterations.

divided into two stages. In the short term ($t = 1$) the farmer takes a decision (U in Fig. 1) considering the stochastic event (K in Fig. 1). In this stage we assume that the farmer can decide on crop allocation and management after considering the stochastic event. Over the long term, ($t > n - 1$), for each branch, the farmer reasons by taking statistical averages into account without stochastic events. In the second iteration, uncertainty related to the stochastic event in the $t = 1$ iteration will be cleared through the recursive process (Blanco and Flichman, 2002). Consequently, each branch will be considered as a new simulation with two stages as in the first iteration and with $t = n - 1$ as a simulation horizon. Simulation stops after n iterations (Fig. 1).

2.2.2. Application of RSP to the Cebalat region

To simulate farmer decisions and analyse cropping system behaviour and performance in the short and long-term, the RSP method was used. Based on the decision-making processes described in Section 2.2.1 and the Cebalat context as described in Section 2.1, the first year of the planning horizon was divided into two decision steps. In the first step (fall), farmers allocate areas with winter crops (oats, barley, wheat, beseem) before knowing the amount of rainfall for the winter period. In the second step (winter), the amount of fall rainfall is known and it is on this basis that the farmer decides on the type and the area allocated to spring-summer crops (alfalfa, maize and sorghum, each of which may be sown either for fodder or grain). Both steps in the decision-making process are modelled. In the first step, the model decides on the cropping pattern, the cropping management parameters (the amounts of irrigation and nitrogen fertiliser), and the area allocated to each crop, while taking rainfall probability into account. In the second step, decisions concern the cropping pattern and the cropping management parameters (amounts of irrigation and nitrogen fertiliser) for the spring-summer period.

The only source of uncertainty is the rainfall during the two periods, i.e. fall and winter. Rainfall variability is taken into account using associated probabilities of occurrence as described in Section 2.4.3, assuming that the probability of each rainfall event does not depend on the previous period.

2.3. The general framework

The general framework used in this paper to test the RSP method and to assess farms' behaviour and sustainability in the Cebalat district consists of two steps:

2.3.1. The CropSyst model

The Cropping Systems Simulation Model (CropSyst, version 3; Stöckle et al., 2003) was used to quantify the relationships between crop production and environmental effects at field level for a range of cropping systems while taking into account information on previously grown crops, and soil and rainfall characteristics. After considering various cropping system models (STICS, APSSIM), CropSyst was chosen both because it has some specific features not available in other models, and because it satisfies most of the conditions needed for this study in one package, namely: (i) CropSyst has been evaluated for the main crops in the Cebalat region at a field scale (plot scale) using measurements of soil and crop variables for the 1999–2000 growing season (Belhouchette et al., 2008), (ii) it includes a generic crop growth simulator, thus facilitating calibration for new species such as berseem, (iii) it can simulate perennial crops such as alfalfa, and (iv) it simulates salt in the soil, including irrigation with fresh and saline water.

2.3.2. Bio-economic farm model

For this study a bio-economic farm model was developed in order to assess the economic and environmental impacts of agricultural and environmental policies and technological innovations on farm and crop system sustainability (Belhouchette, 2004). It is a dynamic model which optimises an objective function to determine which decisions are taken, over a time frame of years. To achieve this hybrid recursive-stochastic method described in Section 2.2 was implemented. It is a primal-based approach, in which technology is explicitly represented (Louhichi et al., 1999), using engineering production coefficients generated from biophysical models (Hengsdijk and Van Ittersum, 2003). These engineering coefficients constitute the essential linkage between the biophysical (CropSyst in this study) and economic models.

Concretely, the bio-economic farm model has a time horizon of 10 years, assuming that long-term decisions are taken according to rainfall probability. In the first simulation year, we considered two decisions, respectively on crop area, crop management and crop products (Section 2.2.2) in the fall and winter, and three states of nature for each decision (rainfall variability, Section 2.4.3). The decision variable is the area of each crop (C), taking into account the previous crop (p), a state of nature (k) and crop water and nitrogen use (i) during 1 year (t): (vector X_{Cpkit}).

For each activity, the crop yields are adjusted over the years for soil salt accumulation by means of the following equation (Mass and Hoffman, 1977):

$$Y_{(C,p,i)} = \alpha_{(C,i)} + \beta_{(C,i)} * EC_{(C,p,i)}$$

where Y is the crop yield (C) depending on the previous crop (p) and the amount of water and nitrogen applied (i); EC is the soil salinity, α and β are estimated for each crop by the CropSyst model and depend on the amount of water and nitrogen applied (i).

The objective function is written as:

$$\text{Maximise NPV} = \sum_k \left[p_k * \sum_t \frac{Z_{kt}}{(1+r)^{t-1}} \right]$$

where NPV represents the expected net present value, p_k is the probability of state of nature k; r is the discount rate and Z_{kt} is the farm income for each state of nature and each year (t).

The bio-economic model maximises this objective function using a recursive process under three types of constraints.

2.3.2.1. Land constraints. For the first year of the planning horizon, the following land constraints apply:

$$\sum_{C_1,p,i} X1_{(C_1,p,k,i)} \leqslant S \quad \text{For } t = 1$$

$$\sum_{C_2,p,i} X2_{(C_2,p,k,i,t)} \geqslant S \quad \text{For } t > 1$$

where $X1$ represents the area allocated to crop rotations in the first decision step (fall) of the first year, and $X2$ the area in the second decision step (winter) of the first year. In each case, the allocated areas must be less or equal to the total available arable land (S).

2.3.2.2. Transfer and rotation constraints. The transfer constraint indicates that the area ($X2$) allocated to each crop in the second decision step of the first year should be equal to the area ($X1$) of the same crop in the first decision step of the same year while taking into account the previous crop (p), production techniques (i), and states of nature (k):

$$\sum_{C_2} X2_{(C_2,p,k,i,t)} = \sum_{C_1} X1_{(C_1,p,k,i,t)} \quad \text{For } t = 1$$

The rotation constraints also show that the area of each crop with a previous crop (p) for the year (t) should be equal to the area allocated to this crop during year ($t-1$).

$\sum_i X2_{(C_2,p,k,i,t)} = rot_{(p,t-1)}$: where rot is the surface allocated to crop p during year ($t-1$).

2.3.2.3. Feed constraints. In order to simulate the development of farm animals, the herd is represented as animal units. The number of animal units has been kept fixed for the entire 10 year simulation timeframe. The parameters and the regional technical coefficient for bovine breeding used for this analysis are those obtained for the 2000/2001 season.

The aim of this constraint is to guarantee an optimal feed ration capable of satisfying the energy demands for bovines by achieving a balance between the animal demands and the available forage resources. The quantities of forage and concentrate produced or purchased are considered in the model by considering the climate, labour and economic constraints. Thus, it's clear for example that in a dried year the amount of purchased forage will be higher than for the wet year.

2.3.3. Methodology summary

Use of the CropSyst-bio-economic farm model involves the following steps:

1. Description of the data base used to run the models and scenarios and specify the rainfall variability and classes.
2. Calibration of the CropSyst model and the bio-economic farm model in order to reproduce respectively the experimentally observed variables (yield, nitrogen leaching and soil salt accumulation) and the observed crop pattern for the selected farm type.
3. Running the calibrated CropSyst for the main crop rotations identified in the Cebalat region and a 30 years simulation timeframe. The purpose of this step is to associate for each activity (crop by rotation, crop management and soil type) average yield and yield variability and externalities (nitrogen leaching, and salt accumulation) over the years.
4. Definition and implementation of the selected scenarios (base and alternative scenarios) and analysis of their impacts at farm scale by running a set of relevant variables through the CropSyst-bio-economic farm model.

2.4. Data base

2.4.1. Experimental data

CropSyst was calibrated using experimental data sets collected for the main crops of the Cebalat region (Belhouchette et al., 2008). This experimental data from the study area provides annual detailed descriptions of management and a set of state variables such

Table 1
Crop management during the 1999–2000 growing season for the field experiments.

Crops	Soil type	Sowing date	Nitrogen amount (kg/ha)	Irrigation amount (mm)	Harvest/clipping
Grains crops					
Wheat	Silt clay loam	19/12/1999	200	0	15/05/2000
Barley	Clay loam	28/12/1999	200	0	25/04/2000
Sorghum	Clay loam	03/07/1999	250	680.4	12/10/1999
Maize	Clay loam	03/07/1999	250	680.4	26/10/1999
Forage crops					
Maize/sorghum	Silt clay loam	03/06/1999	150	220	15/08/1999
Oats	Clay loam	28/12/1999	150	0	25/04/2000
Berseem	Silt clay loam	10/09/1999	200	520	16/11/1999
					25/12/1999
					09/02/2000
					21/03/2000
					08/05/2000
Alfalfa	Loam	01/04/1999	50	1415	03/06/1999
			50		17/04/1999
					11/08/1999
					21/09/1999
					10/11/1999
					28/01/2000
					10/04/2000
					23/05/2000

as main soil characteristics, crop production and soil externalities from 1999 to 2000, for six different fields (Table 1; Belhouchette et al., 2008). For each phenological crop stage, four replications of soil and crop samples were taken, each with a surface area of 1 m^2, successively for each section of the field. Soil salinity, total nitrate and gravimetric soil water content in the root zone were measured in the upper 1 m of soil at increments of 0.20 m in depth. Soil samples were taken at different phenological stages. Leaf area index, above-ground biomass at different phenological stages and yield were measured for each crop. The soils in the area are mainly vertic (silt clay loam), calcareous (loam) and weakly saline (clay loam); in addition weather data were collected on site, including daily rainfall, temperature and radiation.

2.4.2. Survey: field and farm data

In order to identify the main current activities in the investigated region (crop rotations and crop practices: fertilisation, irrigation etc.) a survey, completed by local experts with the use of statistical databases, was carried out in 2000 (Belhouchette, 2004; Belhouchette et al., 2008). In the Cebalat region 64 rotations were identified, with 10 different crops. The principal rotations are soft wheat–maize, barley–sorghum, perennial alfalfa and berseem–fallow. Combined with the results of surveys on management information and climate-soil types, these rotations were defined as the current agricultural activities.

Management information collected for each crop included the different types, quantities, application dates and methods for inputs: sowing, harvesting and tillage events, water management, nutrient management.

In addition, for each crop a set of economic data was specified including the 1999–2000 average producer sale prices and the variable costs. Variable costs were calculated by adding input costs for fertilisers, seeds, irrigation, biocides and the application costs associated with each management event.

Overall, the detailed analysis of the survey showed that farms in the studied area are homogeneous with respect to farm size, land use and farm specialisations (Belhouchette, 2004). Accordingly, only one farm type was selected as being representative of all the farms in the studied area (Table 2).

2.4.3. Rainfall variability and classes

The different rainfall probabilities for the RSP method were estimated using the statistical frequency analysis approach, based on a frequency curve with the ordinate of the curve being the magnitude of the event and the probability of rainfall excess as the abscissa (Haan et al., 1994). Seven rainfall patterns for the fall and winter periods were chosen based on rainfall probabilities (Table 3):

1. The fall period was considered to be wet (F_w), normal (F_n) or dry (F_d) if the total rainfall during the period was respectively between 227 and 189 mm, between 189 and 97 mm and below 97 mm.
2. The winter period was considered to be wet (W_w), normal (W_n) or dry (W_d) if the total rainfall during this period was respectively between 260 and 175 mm, between 175 and 89 mm and below 89 mm.

2.5. Model calibration

2.5.1. The CropSyst model

The crop model was evaluated at the field level. For the calibration, data on yield or biomass for the forage crops in the experimental fields were used to calibrate radiation use efficiency and the biomass-transpiration coefficient by minimising the difference between simulated and observed biomass (Belhouchette et al., 2008).

The measured values of water, nitrogen, and soil salt content in the experimental fields were then compared to the simulated values.

The agreement between simulations and measurements was evaluated using the relative root mean square error (RRMSE) value. Based on this analysis, an RRMSE of 10% can be considered to be an acceptable level for calibration (Loague and Green, 1991).

2.5.2. Bio-economic farm model

The bio-economic farm model was evaluated by comparing the model results for the year 2000 with those of the selected farm type (Section 2.4.2). To check the model's performance two criteria were taken into account: (i) the surface area and yield for each group of crops (cereals, rain-fed forage, irrigated forage and fallow land), and (ii) the capability of the model to reproduce the main farmer decision when the rainfall changes. The evaluation was done by comparing the areas reserved for wheat and rain-fed forage to those of barley and irrigated forage by comparing the dry climate sequences to the wet ones as described in Table 1.

Table 2
Main characteristics of the selected farm type in the Cebalat region for the 2000 (*source:* Belhouchette, 2004).

Specialisation – land use	Mixed
Farm area (ha)	14
Irrigable area (ha)	7.8
Cropping pattern observed	
Cereal (barley and wheat)	1.3
Irrigated forage (beseem and maize forage)	4.6
Fallow	5.7
Rain-fed forage (oats)	1.7
Livestock	
Cow	12
Heifer	4
Calf	3
Heifer for renewal	3
Heifer sold	2

Table 3
Distribution of rainfall frequency by period.

Year	Probability of occurrence by season period (%)		Description
	Fall	Winter	
F_wW_n	20	50	Wet fall and normal winter
F_nW_w	50	20	Normal fall and wet winter
F_nW_n	50	50	Normal fall and normal winter
F_nW_d	50	100	Normal fall and dry winter
F_dW_w	100	20	Dry fall and wet winter
F_dW_n	100	50	Dry fall and normal winter
F_dW_d	100	100	Dry fall and dry winter

2.5.3. Crop production function

The purpose of this step was to associate for each activity, as described in Section 2.4.2, the yields and externalities (N-leaching and the soil salinity accumulation) for a wide range of cropping systems, biophysical conditions and crop practices. To achieve this objective, the CropSyst model was run continuously for a 30 year timeframe (from 1970 to 2000) and then mean values (yield and externalities) were calculated and associated for each activity. CropSyst inputs were set based on:

1. *Management:* Management information collected as described in Section 2.4.2 for all the activities includes the different types, quantities, dates and methods for applying inputs: sowing date, harvest date, N fertilisation dates and amounts and irrigation dates and amounts.
2. *Weather and soil:* The local weather and soil data used for the simulations are specified by soil type as described in Section 2.4.1.
3. *Crop:* The phenological stages, growth, and morphological characteristics such as maximum rooting depth and specific leaf area were computed from the calibration process (Section 2.4.1).

2.6. Simulation scenarios

Two scenarios were developed and compared to analyse the effects of climate variability on farm decision (land use and crop practices) and three performance indicators: leached NO_3–N, accumulated salt in the soil and farmer's income. For both scenarios a 10 year-horizon was set and for each activity the crop yield was adjusted by calculating the soil salt accumulation over a number of years as described in Section 2.3. The updating of the expected net present value is the only difference between the two scenarios. Details (Section 2.3):

Table 4
Model evaluation: error determined by comparing simulated and observed yield/biomass. The observed values were obtained from field experiments during two growing seasons in the Cebalat region.

Crops	Number of observation	Variables	Observed (kg/ha)	Simulated (kg/ha)	RRMSE (%)
Maize	18	Yield	4062	4152	7.0
Sorghum	18	Yield	7950	8098	13.0
Wheat	15	Yield	2390	2446	13.0
Barley	12	Yield	2156	2198	8.0
Oats	12	Biomass	4908	4973	7.0
Alfalfa	24	Biomass	19,767	20,934	18.0
Berseem	15	Biomass	22,720	22,682	3.0

1. The base scenario assumed that farmers prefer present to future income. For this assumption, the current discount rate was set to 10% (Central Bank of Tunisia, 2000).
2. The alternative scenario assumed that farmers value the future as much as the present. For this assumption, the discount rate was set to 0%.

3. Results

3.1. CropSyst evaluation

For all crops, mean simulated yields/biomass were close to the mean measured ones (Table 4). For maize, barley, oats and berseem, the model gave a good estimation of yields/biomass, with a RRMSE lower than 10%. The results were less satisfactory for wheat and maize or sorghum forage crops. The RRMSE values were 13% of the observed average. The lowest correlation was obtained for alfalfa, with an RRMSE of 18%.

The statistical analysis of the simulated soil water content indicated that CropSyst predicted soil water content with acceptable accuracy, giving an RRMSE of less then 10% (Table 5). However, soil water simulation was more accurate in vertic soils in comparison with saline and calcareous soils. Average salt concentration of the top 1 m soil layer was simulated and compared to measured values (Table 5). The RMMSE was better for the vertic soil than for the saline and calcareous soils. For the vertic soil, CropSyst overestimated soil salinity concentration (data not shown).

Table 5 also shows a comparison between measured and simulated nitrogen in the soil profile. These results demonstrate that the model simulated soil nitrate dynamics with satisfactory accuracy for the vertic and calcareous soils, with an RRMSE lower than 25%. However, the model results were not good for the saline soil,

Table 5
Model evaluation: RRMSE data from a comparison of observed data and simulated values for water, salts and nitrogen soil content The observed values were obtained from field experiments during two growing seasons in the Cebalat region.

	Soil	*N*	Observed average	Predicted average	RRMSE
			(m^3/m^3)	(m^3/m^3)	(%)
Water	Vertic	187	0.2	0.2	0.085
	Calcareous	165	0.17	0.17	0.095
	Saline	86	0.16	0.16	0.096
			(dS/m)	(dS/m)	(%)
Salts	Vertic	60	5.09	5.18	0.099
	Calcareous	48	4.87	4.85	0.028
	Saline	19	4.61	4.8	0.076
			(kg/ha)	(kg/ha)	(%)
Nitrogen	Vertic	48	5.16	5.18	0.24
	Calcareous	20	4.76	4.77	0.18
	Saline	16	3.43	2.67	0.54

giving an RRMSE of 54%. It must be pointed out that measured field data of soil nitrogen content were affected by large variability, which increased the uncertainty of the model evaluation (data not shown).

3.2. Evaluation of the bio-economic farm model

The model accurately reproduces the percentage surface area of each type of crop (Table 6). The difference between observed and simulated values is usually less than 30%. The same conclusion is valid for crop production. In fact, Table 6 also shows that the difference between simulated and observed production (average yield) of cereal crops (rain-fed wheat and berley), irrigated forage (berseem, and maize forages and oats) and rain-fed forage (oats) is usually less than 15%.

The model reproduces correctly the main farmer decision in Mediterranean regions with a decrease of the area reserved for wheat and rain-fed forage and an increase of those of barley, oats and irrigated forage. Table 7 shows the model results for the area reserved for each crop by rainfall sequence for the base scenario, which changed depending on the climatic conditions. Indeed, the area allocated for wheat decreased from 4.7 ha (F_wF_n) to 2.8 ha when winter and fall became drier (F_dW_d), while the area assigned to barley increased from 0 ha to 2.3 ha. This means that the model reduces risk by planting more barley when the fall is very dry and winter becomes drier (F_dW_w, F_dW_n, F_dW_d) because barley is more resistant to drought than wheat. The area reserved for rain-fed forage increased when the fall was drier (F_d) except for the sequences (F_dW_n). The same tendency was observed for irrigated forage, where the area reserved for those crops increased progressively when the winter and the fall became drier. The area set aside as fallow land strongly decreased when the fall became drier (F_d). This seems to be logical because fallow land is usually used in rotation with wheat, which also decreases when the fall is drier.

3.3. Evaluation of three performance indicators: soil salinisation rate, leached NO_3–N, and farmer's income

3.3.1. Soil salinisation rate

The evolution curves of the soil salinisation rate (Fig. 2a) and the state of nature (Fig. 2b) over the ten-year simulation period were approximately the same for the base and alternative scenarios. The same figures show that for both scenarios, the soil salinity does not change significantly from year to year and is more often higher for the base scenario than for the alternative one. This result seems to be due to the number of crops selected (crop diversity), the area per crop and the difference in the amount of irrigation applied. In fact, the crop diversity and the average area reserved for each crop used for the 10 simulation years by climatic sequences shows a difference between the two types of scenario. The crop diversity is about 9% higher in the alternative scenario (except for F_wW_n and F_dW_d) as compared to the base one (data not shown). Thus, for the base scenario the area reserved for irrigated forage is usually higher than for the alternative one except for F_wW_n and F_dW_w. Inversely, the area reserved for the rain-fed crops is higher for the alternative scenario than for the base one.

Table 7
Area reserved for each crop by climatic sequence. Each value represents an average of 10 years of simulation.

	Area (ha)				
	Wheat	Barley	Rain-fed forage	Irrigated forage	Fallow
F_wW_n	4.72	0.0	1.1	1.4	6.6
F_nW_w	4.3	0.2	1.7	1.9	5.8
F_nW_n	4.3	0.1	1.7	1.8	6.0
F_nW_d	4.2	0.1	1.8	1.8	6.0
F_dW_w	3.1	1.7	2.3	2.0	5.2
F_dW_n	2.8	2.7	1.7	2.2	5.1
F_dW_d	2.8	2.3	2.1	2.0	5.2

Fig. 3 illustrates the amount of irrigation used in each climate sequence. Two conclusions were reached: (i) when the fall is rainy (F_wW_n) the amount of irrigation is almost the same for the two types of scenario. In this case we can assume that there is enough rainfall to leach the salts out of the root zone; (ii) for the rest of climatic sequences the amount of irrigation for the alternative scenario is higher than for the base one. It would appear that the same amount of irrigation is used not for crop requirements, but for leaching out soil salinity. This difference reaches 55% for the sequences F_dW_w and F_dW_n.

The area reserved for each irrigated crop for the seven climate sequences increases, except for berseem, when the winter or fall is drier (data no shown; from 7.5 ha for F_wW_n to 10.5 ha for F_dW_d). The result is the same for the two types of scenario. For example, the irrigated sorghum and maize forage (summer crops) area increases from 2.6 ha to 5.3 ha when the winter and fall gradually become drier. Berseem, an irrigated winter crop, disappears when the fall and winter seasons become drier and the area under alfalfa is increased to replace it. Table 8 sums up the amount of irrigation by crop and by hectare. For all crops the amount of irrigation by crop and by hectare is higher for the alternative scenario. This difference is 63% for the oats and confirms the idea that irrigation is used for soil salinity leaching in order to enable long-term productivity.

3.3.2. Nitrate leaching

The evolution of the average nitrate lixiviation over the 10 years of simulation (Fig. 4) and the variation of nitrate leaching expressed by climate sequences show that for both scenarios the nitrate leaching is less than 25 kg/ha. Thus, even though in the alternative scenario the amount of irrigation is higher than in the base one (Section 3.3.1), the nitrate losses do not increase significantly. In fact, the largest difference in term of nitrate leaching between the two scenarios was observed for the F_nW_w climate sequence (10 kg/ha). Nevertheless, the difference in nitrate leaching between the base scenario and the alternative one could be high for some crops, i.e. the nitrate leaching for maize crop is 40 and 10 kg/ha for the alternative and the base scenarios respectively. The same trend was observed for the other irrigated crops

Table 6
Validation of the bio-economic farm model: comparison of simulated and observed data. Cereal (barley and wheat), irrigated forage (berseem and maize forage), rain-fed forage (oats).

Crops	Area (ha)			Production (kg/ha)		
	Model	Survey	Difference (%)	Model	Survey	Difference (%)
Cereal	0.9	1.3	26.0	2163	2520	14.0
Irrigated forage	4.6	4.6	1.7	45,944	42,300	8.6
Fallow	5.9	5.7	2.0	–	–	–
Rain-fed forage	2.1	1.7	18.0	29,147	31,500	7.4

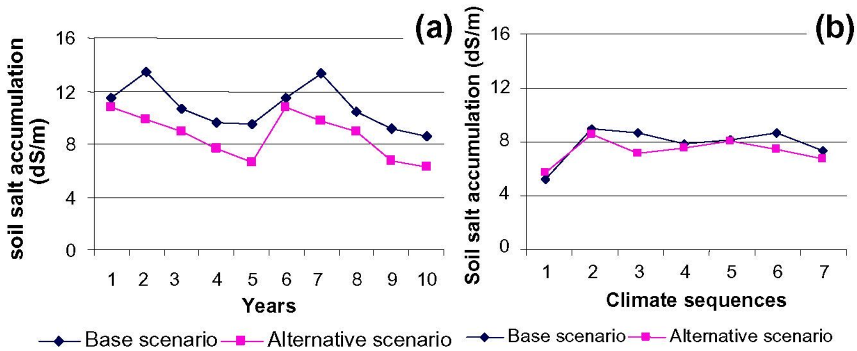

Fig. 2. Evolution of the salinisation rate over 10 years of simulation (a) and by state of nature (b) for the base scenario and the alternative scenarios.

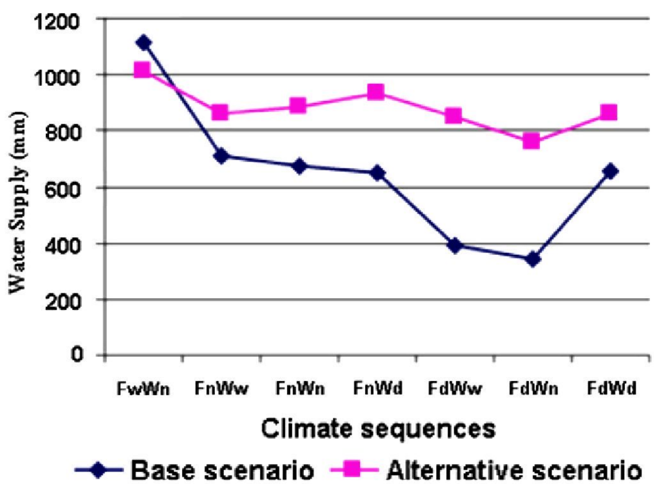

Fig. 3. Amount of irrigation by climate sequence for the base and the alternative scenario.

(data not shown). This difference is due mainly to the amounts of nitrogen fertiliser and irrigation which are systematically higher in the alternative scenario than in the base one as shown in Table 9.

3.3.3. Farmer income

Fig. 5 compares the farmer income trend for the two types of scenario with a high variability between years due mainly to rainfall variability which is normally the case for Mediterranean conditions. The income variation for the two scenarios is similar but income difference between the alternative and base scenarios increases over time to attain 45% after 10 years due to lower soil salinisation associated with a more diversified cropping pattern and surplus water application for leaching of salts (Section 3.3.1). The amount of irrigation is higher for the alternative scenario compared to the base one, and for all climate sequences that the gross margin is more important in this case than for the base one. Table 9 gives a good illustration of this dilemma. Soil rate salinisation is lower in the alternative scenario than in the base one (except for the rainy sequence F_wW_n). This may be explained by the fact that profit caused by the increase of crop yields is higher than the costs of supplying extra water and nitrogen observed for the alternative

Table 8
Comparison of the area and the amount of water applied for each irrigated crop for the two types of scenario. Each value represents the mean of all climatic sequences and 10 years of simulation.

Crops	Area (ha)			Amount of irrigation (mm)		
	Base	Alternative	Difference (%)	Base	Alternative	Difference (%)
Sorghum forage	26.2	33.0	20.7	378.0	419.2	9.8
Alfalfa	27.4	29.7	7.6	942.8	1330.6	29.1
Oats	6.4	8.2	22.5	218.2	590.0	63.0
Maize forage	0.8	1.2	34.4	950.0	1260.0	24.6
Berseem	6.8	0.7	−868.6	771.4	897.5	14.0

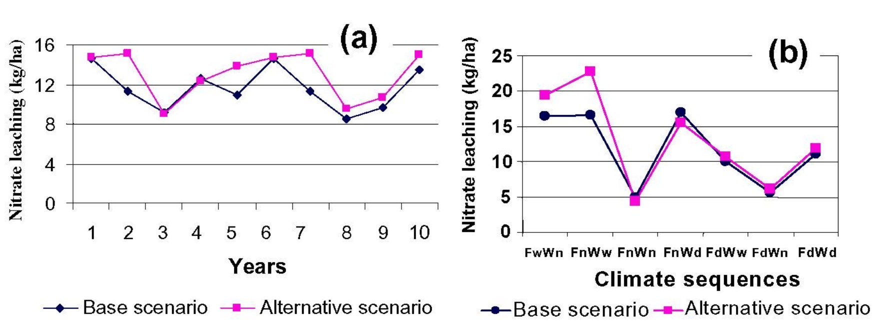

Fig. 4. Evolution of nitrate leaching over the 10 years of simulation (a) and of nitrate leaching by climate sequence (b) for the base and alternative scenarios.

Table 9
Comparison of the amount of nitrogen fertiliser applied, irrigation, nitrogen leaching, soil salinisation rate and gross margin for the two types of scenarios and for each rainfall sequence.

	Fertilisation (kg/ha)		Irrigation (mm)		Nitrogen leached (kg/ha)		Salinisation rate (dS/m)		Grosse margin (Dinar)	
	Base	Alternative	Base	Alternative	Base	Alternative	Base	Alternative	Base	Alternative
F_wW_n	131.2	139.0	1114.7	1015.1	18.0	19.4	5.1	3.8	19,840	19,570
F_nW_w	138.6	155.2	713.9	860.6	15.4	22.8	8.9	5.2	15,636	15,998
F_nW_n	133.0	144.1	673.9	885.5	4.4	4.4	8.5	4.8	14,425	15,177
F_nW_d	130.9	146.6	653.9	934.3	14.9	15.6	7.7	4.6	13,375	14,676
F_dW_w	128.0	128.6	389.8	851.5	9.8	10.7	8.0	5.6	13,597	13,823
F_dW_n	127.4	124.3	342.9	760.1	4.7	6.2	8.5	4.9	14,388	14,415
F_dW_d	130.8	131.3	660.2	863.6	9.6	11.9	7.2	4.6	13,045	13,105

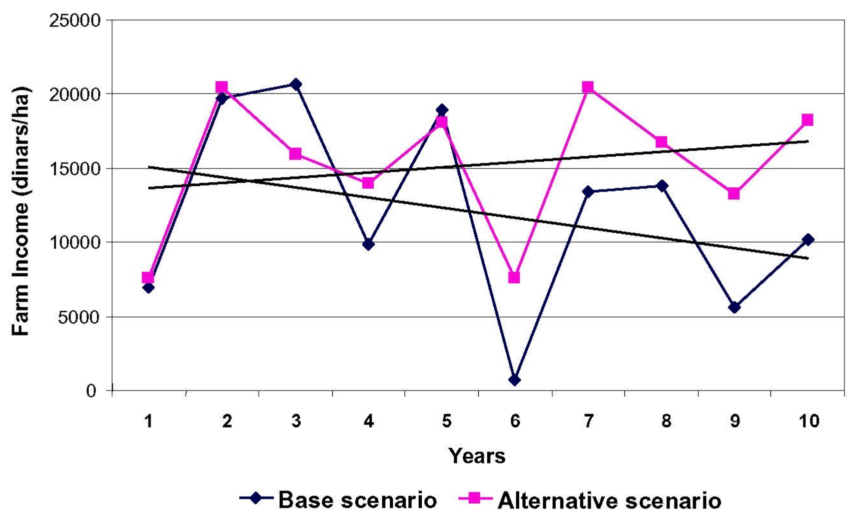

Fig. 5. Simulated farm income over 10 years and testing of the alternative (0%) and base (10%) scenarios.

scenario, i.e. the mean simulated reduction yields after 10 simulation years of winter wheat and irrigated maize forage is respectively about 12% and 20% when the base scenario is compared to the alternative one (data not shown).

4. Discussion

4.1. Discussion of results

To prevent salt from accumulating in soil, leaching part of this salt through irrigation is essential for agriculture, especially in arid regions (Ritter, 1989; Rhoades et al., 1974; Smith and Hancock, 1986). However, this strategy can cause nitrogen leaching. The principal reason for this is a high level of irrigation used in the alternative scenario. Moreover, the decrease in the soil salinisation rate observed in the alternative scenario is accompanied for most crops by an increase in yield such as described for winter wheat and maize forage in Section 3.3.3. In fact, when salt increases above a threshold level, both the growth rate and ultimate size of crop plants progressively decrease (Rajak et al., 2006; Botía et al., 2005). However, the threshold and the rate of growth reduction vary widely among different crop species. Some crops such as maize and berseem are highly sensitive to the salinity (threshold about 2.5 dS/m). Other crops such as wheat, sorghum and barley are more tolerant (threshold about 7.5 dS/m) (Maas and Grattan, 1999). This difference between species explains that the yield reduction observed for maize forage is 8% higher than for wheat when the base scenario is compared to the alternative one.

The increase of yield due to the decrease of salt in soil explains the difference in the amount of nitrogen applied by the two types of scenario. In fact, for all climate sequences, more nitrogen fertiliser is implemented for the alternative scenario. This result explains the higher nitrogen leaching observed for some crops for alternative scenario in comparison with the base one. This result is in agreement with numerous studies (Powlson, 1988; Carpenter et al., 1998; Di and Cameron, 2002) thus indicating that leaching of soil NO_3^- from the plant root zone to groundwater is mainly determined by two important factors: the amount of NO_3^- used for fertilisation and the irrigation volume.

4.2. Methodology evaluation

The modeling chain of the CropSyst-bio-economic model was successfully applied to derive and assess short and long-term cropping systems in the Cebalat region. In a Mediterranean region assessing the sustainability of a cropping system involves a complex set of farmer decisions depending on biophysical (climate, soil and cropping systems) and socio-economic (price, quota...) conditions. To achieve such an objective a recursive stochastic programming method was developed and implemented to determine a base for the bio-economic model. The method proved that it was possible to represent the evolution of farm decisions within a given year and over a period of years by taking into account a wide range of (i) biophysical conditions (soil, rainfall), (ii) types of crop, land use or agro management system (cereal, annual forage crops, perennial forage crops), (iii) types of production (fodder, grain) and (iv) types of socio-economic context (labour, price). This methodology could also be re-used to simulate different scenarios combining biophysical, crop diversity and socio-economic conditions (e.g. price liberalisation, water quotas, etc.) as well as new techniques that may be released by industry and extension services (e.g. new varieties resistant to major diseases and soil salt accumulation, new cropping techniques such as conservation agriculture or organic farming promoted in a region etc.) (Belhouchette et al., in press).

In this study to assess the sustainability of cropping systems, a considerable effort was made to collect and harmonise data from various sources (from experiments, surveys on farm management practices, etc.), for the different models (CropSyst, bio-economic) and different disciplines (agronomy, economy). Combining experimental, statistical and expert knowledge, the data allowed us to evaluate successfully the CropSyst and bio-economic models quantitatively and to run base and alternative scenarios.

On the other hand, assuming a 0% discount rate (alternative scenario), an economic and environmentally sustainable agriculture was achieved following analysis of quantifiable indicators.

4.3. Which policy would lead to sustainable farming systems?

In the south part of the Mediterranean region is often advised to establish high prices for irrigation water in order to save water (Thabet et al., 1999). This strategy may induce negative effects on salinity. In fact, reducing water use may lead to further soil degradation. This study shows the danger of generalising usual recommendations concerning these complex environmental and natural resource issues.

Implementing two discount rates is simply an intellectual exercise to mirror farmers' behaviour according to two different strategies: search for short term versus long term profit. In real life, it would be necessary to establish agricultural policies producing an equivalent effect on farmers' behaviour such as enforcing a 0% discount rate (sustainable scenario), which is not so obvious.

While water tariffs are important to recover the cost of delivering water and to provide incentives for adopting water saving techniques (Abbes, 2004), this should not be the only policy option to manage the reuse of wastewater for irrigation purposes. In arid regions with soil salinity problems, promoting the application of a leaching water fraction would be a more sustainable policy option.

In peri-urban areas, reusing wastewater for irrigation can be viewed as a way to increase water supply. In Tunisia, a national reuse programme started in the early 1980s to increase availability of water resources (Qadir et al., 2010). Most wastewater receives secondary biological treatment and is used for irrigation. Public policies are already promoting the reuse of urban wastewater, but these policies often lack enough knowledge to apply the most effective option for each specific situation.

In arid regions where water supply is not a limiting factor because urban wastewater is abundant, applying additional water for leaching purposes could enhance long-term soil productivity. Several scenarios focusing at irrigation sustainability could then be tested with the current modelling chain, namely involving (i) promotion of water users' associations (Le Grusse et al., 2006), (ii) extension programmes to help farmers to adopt suitable farm-level practices, and (iii) use of incentives to adopt technologies that save water at field level while prevent salt accumulation in the soil (Mailhol et al., 2004).

5. Conclusion

The aim of this study was to investigate the sustainability of farming systems in the Cébalat irrigation district of Tunisia, which uses recycled urban wastewater to irrigate forage and cereal crops. This paper addresses the challenging topic of agricultural sustainability by means of a bio-economic approach, which links a biophysical model and an economic optimisation model.

The bio-economic model allowed us to test our initial hypothesis that farmers' preference for short-term profit would gradually lead to a degradation of soil productivity.

Assuming a realistic discount rate of 10% (base scenario), our model closely reproduces the real system. Simulation beyond the normal planning horizon shows that there is no guarantee of the production system being sustained. The model is able to predict soil degradation due to long-term salinisation. This problem is related mainly to the lack of irrigation and could be mitigated with using irrigation water for leaching purposes. Concerning nitrate pollution, the only conclusion is that for both scenarios no nitrogen leaching risk was observed.

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